

ADAPTIVE EDGE DETECTION AND ENHANCEMENT FOR IMAGE PROCESSING

PRIORITY AND RELATED APPLICATIONS

The present application claims priority to provisional patent application entitled, "Video Processing Method with General and Specific Applications," filed on July 11, 2000 and assigned U.S. Application Serial No. 60/217,301. The present application is also related to non-provisional application entitled, "System and Method for Calculating an Optimum Display Size for a Visual Object," (attorney docket number 07816-105002) filed on July 11, 2001 and assigned U.S. Application Serial No. _____; and non-provisional application entitled, "Video Compression Using Adaptive Selection of Groups of Frames, Adaptive Bit Allocation, and Adaptive Replenishment," (attorney docket number 07816-105004) filed on July 11, 2001 and assigned U.S. Application Serial No. _____.

FIELD OF THE INVENTION

The present invention relates to the processing of images and more specifically relates to the improvement of images by detecting an edge dividing areas of substantially constant image intensity and enhancing the edge by amplifying the intensity difference between the detected edge and the adjacent areas.

BACKGROUND OF THE INVENTION

Recent advancements in communication technologies have enabled the widespread distribution of data over communication mediums such as the Internet and broadband cable systems. This increased capability has lead to increased demand for the distribution of a diverse range of content over these communication mediums. Whereas early uses of the Internet were often limited to the distribution of raw data, more recent advances include the distribution of HTML-based graphics and audio files.

More recent efforts have been made to distribute video media over these communication mediums. However, because of the large amount of data needed to represent a video presentation, the data is typically compressed prior to

5 distribution. Data compression is a well-known means for conserving transmission resources when transmitting large amounts of data or conserving storage resources when storing large amounts of data. In short, data compression involves minimizing or reducing the size of a data signal (e.g., a data file) in order to yield a more compact digital representation of that data signal. Because digital representations of audio and
10 video data signals tend to be very large, data compression is virtually a necessary step in the process of widespread distribution of digital representations of audio and video signals.

Fortunately, video signals are typically well suited for standard data compression techniques. Most video signals include significant data redundancy.

15 Within a single video frame (image), there typically exists significant correlation among adjacent portions of the frame, referred to as spatial correlation. Similarly, adjacent video frames tend to include significant correlation between corresponding image portions, referred to as temporal correlation. Moreover, there is typically a considerable amount of data in an uncompressed video signal that is irrelevant. That
20 is, the presence or absence of that data will not perceptibly affect the quality of the output video signal. Because video signals often include large amounts of such redundant and irrelevant data, video signals are typically compressed prior to transmission and then expanded (i.e., decompressed) again after transmission.

Generally, the distribution of a video signal includes a transmission
25 unit and a receiving unit. The transmission unit will receive a video signal as input and will compress the video signal and transmit the signal to the receiving unit. Compression of a video signal is usually performed by an encoder. The encoder typically reduces the data rate of the input video signal to a level that is predetermined by the capacity of the transmission or storage medium. For example, for a typical
30 video file transfer, the required data rate can be reduced from about 30 Megabits per second to about 384 kilobits per second. The compression ratio is defined as the ratio between the size of the input video signal and the size of the compressed video signal. If the transmission medium is capable of a high transmission rate, then a lower compression ratio can be used. On the other hand, if the transmission medium is

5 capable of a relatively low transmission rate, then a higher compression ratio can be used.

After the receiving unit receives the compressed video signal, the signal must be decompressed before it can be adequately displayed. The decompression process is performed by a decoder. In some applications, the decoder
10 is used to decompress the compressed video signal so that it is identical to the original input video signal. This is referred to as lossless compression, because no data is lost in the compression and expansion processes. The majority of encoding and decoding applications, however, use lossy compression, wherein some predefined amount of the original data is irretrievably lost in the compression and expansion process. In
15 order to expand the video stream to its original (pre-encoding) data size, the lost data must be replaced by new data. Unfortunately, lossy compression of video signals will almost always result in the degradation of the output video signal when displayed after decoding, because the new data is usually not identical to the lost original data. Video signal degradation typically manifests itself as a perceivable flaw in a displayed
20 video image. These flaws are typically referred to as noise. Well-known kinds of video noise include blockiness, mosquito noise, salt-and-pepper noise, and fuzzy edges. The data rate (or bit rate) often determines the quality of the decoded video stream. A video stream that was encoded with a high bit rate is generally a higher quality video stream than one encoded at a lower bit rate.

25 Therefore, there is a need in the art for image enhancement that offsets some of the well-known image flaws caused by the conventional encoding and decoding processes. The image enhancement should be adaptive to provide varying degrees of enhancement, based on various constraints, such as transmission bit rate and image brightness.

30

SUMMARY OF THE INVENTION

The present invention improves image quality by detecting and enhancing edges in an image. An edge is a portion of an image separating two regions of substantially constant image intensity. An image can be examined on a
35 pixel-by-pixel basis to find a candidate edge pixel. Candidate edge pixels are pixels

5 that have an image intensity that differs from the intensity of adjacent pixels by more
than a predefined threshold amount. When a candidate edge pixel is found, a
determination can be made as to whether the candidate edge pixel resides on a true edge.
A candidate edge pixel resides on a true edge when one or more other candidate edge
pixels are adjacent and/or contiguous with the initial candidate edge pixel. A true
10 edge can be enhanced by amplifying the image intensity differences between the
pixels on the true edge and those adjacent pixels not on the true edge. The present
invention also provides a novel image processing filter for eliminating well known
noise from an image. The image processing filter can further improve edge
enhancement by eliminating such noise prior to the edge detection and enhancement.

15 In one aspect of the present invention, a method is provided for
processing an image. A first image intensity associated with a subject image portion
is compared with a second image intensity associated with an adjacent image portion.
An image intensity difference between the first image intensity and the second image
intensity is determined. The subject image portion is classified as a candidate edge
20 portion in response to a determination that the first image intensity is less than the
second image intensity and a determination that the image intensity difference is
greater than a predetermined threshold image intensity difference. A determination is
made as to whether the candidate edge portion is a true edge portion. The subject
image portion is associated with a third image intensity, wherein the third image
25 intensity is less than the first image intensity.

In another aspect of the present invention, a system for enhancing a
digitized image is provided. The system includes a decoder operative to receive an
encoded digitized image and to expand the encoded digitized image to generate a
decoded digitized image. The system also includes a post-processing unit operative to
30 filter the decoded digitized image to process image flaws. The system also includes
an edge enhancer operative to detect an edge in the decoded digitized image and to
enhance the edge in the decoded digitized image.

In yet another aspect of the invention, a method is provided for
detecting and enhancing an edge in a decoded digitized image. A first image intensity
35 is determined, where the first image intensity is associated with a first pixel in the

5 decoded digitized image. A second image intensity associated with a second pixel in the decoded digitized image is also determined. A third image intensity associated with a third pixel in the decoded digitized image is also determined. The first pixel is classified as a first candidate edge pixel in response to a determination that the first image intensity is less than the second image intensity and is less than the third image
10 intensity. A determination is made as to whether the first pixel is adjacent to a second candidate edge pixel. Another determination is made as to whether the second pixel is adjacent to a third candidate edge pixel. The first pixel is classified as a true edge pixel in response to a determination that the first pixel is adjacent to the second candidate edge pixel and the second candidate edge pixel is adjacent to the third candidate edge pixel. A fourth image intensity is associated with the first pixel, where
15 the fourth image intensity is lower than the first image intensity.

BRIEF DESCRIPTION OF THE DRAWINGS

20 Figure 1a depicts an exemplary image that has been compressed and decompressed and includes a fuzzy edge.

Figure 1b depicts an enlarged view of the fuzzy edge of the image of Figure 1a.

Figure 1c depicts an enlarged view of the image of Figure 1a after the fuzzy edge has been processed by an exemplary embodiment of the present invention.

25 Figure 2 is a flowchart depicting an exemplary method for coding, transmitting, and decoding a video stream.

Figure 3 is a block diagram depicting a conventional system for encoding a video stream.

30 Figure 4 depicts a conventional decoding system for receiving an encoded video stream and providing decoded video and audio output.

Figure 5 is a decoding system that is an exemplary embodiment of the present invention.

Figure 6a depicts an exemplary pixel matrix in enhanced and in unenhanced images.

5

Figure 6b depicts an exemplary pixel intensity graph illustrating the relationship between adjacent pixels in enhanced and in unenhanced images.

Figure 7 is a flow chart depicting an exemplary method for examining and enhancing the pixels of a digitized image.

Figure 8 is a flow chart depicting an exemplary method for detecting 10 an edge in an image.

Figure 9 is a flow chart depicting an exemplary method for detecting and enhancing true edge pixels.

Figure 10 is a graph depicting an embodiment of the present invention in which the intensity slope adjustment is adapted to match the image quality of an 15 unenhanced image.

Figure 11 is a graph depicting an adaptive slope adjustment utilized in another alternative embodiment of the present invention.

Figure 12a is a block diagram depicting the presence of blockiness 20 noise in an unenhanced image.

Figure 12b is a graph depicting the adaptive performance of a blockiness filter that is an exemplary embodiment of the present invention.

Figure 13 is a block diagram depicting the adaptive performance of a salt-and-pepper noise filter that is an exemplary embodiment of the present invention.

Figure 14a is a block diagram depicting an exemplary group of 25 adjacent pixels that may be examined and filtered for mosquito noise by an exemplary embodiment of the present invention.

Figure 14b is a graph depicting the adaptive performance of a mosquito noise filter that is an exemplary embodiment of the present invention.

30 DETAILED DESCRIPTION

Figure 1a depicts an exemplary image that has been compressed and decompressed and includes a fuzzy edge. The image 100 has been compressed and decoded, such that it has various perceivable flaws. For example, a line 102 that should be a solid black line, includes lighter colored pixels. These lighter colored 35 pixels have been created during the compression and decoding processes as a result of

5 an attempt to represent a diagonal line within the constraints of a pixel matrix. The line 102 is an edge dividing two areas of substantially uniform image intensity 116, 118. Figure 1b depicts an enlarged line 104 that is simply a magnified depiction of the line 102. The magnified line 104 exaggerates the perceivable flaws of line 102. For example, pixel 110 should be black (i.e., low image intensity), rather than gray 10 108 (i.e., relatively higher image intensity), rather than gray (i.e., relatively lower image intensity). As a result of these perceivable flaws, among others, line 102 is not a solid black line, but is, instead, a broken black line including gray pixels.

An embodiment of the present invention processes the image 100 to 15 enhance image edges, such as that represented by line 102. Figure 1c depicts an enlarged line 106 that is simply a magnified depiction of the line 102 after the line has been enhanced by an exemplary embodiment of the present invention. That is, magnified line 104 can be processed to generate enhanced line 106. While the gray pixel 108 has been substantially unchanged to generate gray pixel 114, gray pixel 110 20 has been modified to generate black pixel 112. Thus, the enhanced line 106 has a solid, black representation in an enhanced representation of the image 100. In an alternative embodiment of the present invention, gray pixel 114 (and others like it) could be changed to a white pixel to further enhance the edge represented by the enhanced line 106.

25 In an exemplary embodiment of the present invention, the image 100 is examined on a pixel-by-pixel basis. Edges are detected by comparing a subject pixel with its adjacent pixels. In the event that a subject pixel has an image intensity (e.g., luminance, chrominance) that is significantly different than that of an adjacent pixel, the subject pixel is identified as a potential edge pixel or a candidate edge pixel. An 30 exemplary embodiment of the present invention may determine that a true edge exists where three or more candidate edge pixels form a contiguous unit. When a true edge has been identified, the edge can be enhanced by decreasing and/or increasing the image intensity of one or more pixels on or near the true edge.

Fig. 2 is a flowchart depicting an exemplary method for coding, 35 transmitting, and decoding a video stream. One application for which the described

5 exemplary embodiment of the present invention is particularly suited is that of video stream processing. A video stream is simply a series of related images that have been connected in a series to create the perception that objects in the image series are moving. Because of the large number of separate images that are required to produce a video stream, it is common that the series of images will be digitized and
10 compressed, so that the entire video stream requires less space for transmission or storage. The process of compressing such a digitized video stream is often referred to as “encoding.” Among other things, encoding a video stream typically involves removing the irrelevant and/or redundant digital data from the digitized video stream. Once the video stream has been so compressed, the video stream must usually be
15 expanded before it can be properly displayed. The flow chart of Fig. 2 depicts the steps that are generally followed to encode, decode, and display a video stream.

The method of Fig. 2 begins at start block **200** and proceeds to step **202**. At step **202**, the input video stream is encoded. As described, the encoding process involves, among other things, the compression of the digitized data making up the input video stream. The method proceeds from step **202** to step **204**. At step **204**, the encoded video stream is transmitted. Often this transmission can be made over conventional broadcast infrastructure, but could also be over broadband communication resources and/or internet-based communication resources.

The method proceeds from step **204** to step **206**. At step **206**, the received, encoded video stream is stored. As described above, the compressed video stream is significantly smaller than the input video stream. Accordingly, the storage of the received, encoded video stream requires fewer memory resources than storage of the input video stream would require. This storage step may be performed by a computer receiving the coded video stream over the Internet. Those skilled in the art
25 will appreciate that step **206** could be performed by a variety of well-known means and could even be eliminated from the method depicted in Fig. 2. For example, in a real-time streaming video application, the video stream is typically not stored prior to
30 display.

The method proceeds from step **206** to step **208**. At step **208** the video stream is decoded. Decoding a video stream includes, among other things, expanding

5 the encoded video stream to its original data size. That is, the encoded video stream is expanded (i.e., decompressed) so that it is the same size as the original input video stream. The irrelevant and/or redundant video data that was removed in the encoding process is replaced with new data. Various, well-known algorithms are available for decoding an encoded video stream. Unfortunately, these algorithms are typically
10 unable to return the encoded video stream to its original form without some perceivable image degradation. Consequently, a decoded video stream is typically filtered by a post-processing filter to reduce flaws (e.g., noise) in the decoded video stream.

Accordingly, the method of Fig. 2 proceeds from step 208 to step 210,
15 wherein the video stream is filtered and enhanced. This step may be performed using a conventional post-processing filter to reduce noise such as mosquito noise, salt-and-pepper noise, and blockiness. Any edges found in the images of the decoded video stream also may be enhanced according to an exemplary embodiment of the present invention. Once the video stream has been decoded, filtered, and enhanced, it is
20 suitable for displaying. The method of Fig. 2 proceeds from step 210 to step 212 and the enhanced video stream is displayed. The method then proceeds to end block 214 and terminates.

Figure 3 is a block diagram depicting a conventional system for encoding a video stream. The encoding system 300 receives a video input 302 and an
25 audio input 304. The video input is typically a collection of digitized images that are linked together in series. The audio input 304 is simply the audio signal that is associated with the series of images making up the video input 302.

The video input 302 is first passed through a pre-processing filter 306 that, among other things, filters noise from the video input 302 to prepare the input
30 video stream for encoding. Unfortunately, conventional pre-processing filters will often blur (soften) edges in the images of the video stream as an unintended result of noise filtration. Edge blurring is a well-known characteristic of pre-processing filters. The pre-processed video stream is then passed to the video encoder 310. The video encoder compresses the video signal by eliminating irrelevant and/or redundant data
35 from the input video signal. The video encoder 310 may reduce the input video signal

5 to a predetermined size to match the transmission requirements of the encoding system 300. Alternatively, the video encoder 310 may simply be configured to minimize the size of the encoded video signal. This method might be used, for example, to maximize the storage capacity of a storage medium (e.g., hard drive).

In a similar fashion, the audio input 304 is compressed by the audio encoder 308. In some conventional encoding systems, the audio signal also may be subjected to a pre-processing filter (not shown). The encoded audio signal is then passed with the encoded video signal to the video stream multiplexer 312. The video stream multiplexer 312 combines the encoded audio signal and the encoded video signal so that the signals can be subsequently separated and played-back substantially simultaneously. After the encoded video and encoded audio signals have been combined, the encoding system outputs the combined signal as an encoded video stream 314. The encoded video stream 314 is thus prepared for transmission, storage, or other processing as needed by a particular application. Often, the encoded video stream 314 will be transmitted to a decoding system that will decode the encoding video stream 314 and prepare it for subsequent display.

Figure 4 depicts a conventional decoding system for receiving an encoded video stream and providing decoded video and audio output. The decoding system 400 receives an encoded video stream 402 as input to a video stream demultiplexer 404. The video stream demultiplexer separates the encoded video signal and the encoded audio signal from the encoded video stream 402. The encoded video signal is passed from the video stream demultiplexer 404 to the video decoder 406. Similarly, the encoded audio signal is passed from the video stream demultiplexer 404 to the audio decoder 410. The video decoder 406 and the audio decoder 410 expand the video signal and the audio signal to a size that is substantially identical to the size of the video input and audio input described above in connection with Figure 3. Those skilled in the art will appreciate that various well-known algorithms and processes exist for decoding an encoded video and/or audio signal. It will also be appreciated that most encoding and decoding processes are lossy, in that some of the data in the original input signal is lost. Accordingly, the video decoder

5 406 will reconstruct the video signal with some signal degradation is often receivable as flaws in the output image.

The post-processing filter 408 is used to counteract some of the well-known noise found in a decoded video signal that has been encoded and/or decoded using a lossy process. Examples of such well-known noise types include mosquito 10 noise, salt-and-pepper noise, and blockiness. The conventional post-processing filter 408 includes well-known algorithms to detect and counteract these and other known noise problems. The post-processing filter 408 generates a filtered, decoded video output 412. Similarly, the audio decoder 410 generates a decoded audio output 414. The video output 412 and the audio output 414 may be fed to appropriate ports on a 15 display device, such as a television, or may be provided to some other display means such as a software-based media playback component on a computer or a static display device such as a printer. Alternatively, the video output 412 and the audio output 414 may be stored for subsequent display.

Figure 5 is a decoding system that is an exemplary embodiment of the 20 present invention. The exemplary decoding system 500 includes many of the components found in the conventional decoding system 400 (Fig. 4) and also accepts an encoded video stream 502 as input. As with the system of Figure 4, the encoded video stream 502 is sent through a video stream demultiplexer 504 and separated for decoding by a video decoder 506 and an audio decoder 510.

25 However, the exemplary decoding system 500 includes a specialized post-processing filter 508. The specialized post-processing filter 508 includes enhanced algorithms for counteracting the effects of mosquito noise, salt-and-pepper noise, and blockiness. These specialized algorithms enable the post-processing filter 508 to adapt the level of noise reduction to match the characteristics of the decoded 30 video signal. This aspect of the post-processing filter 508 will be described in more detail in connection with Figures 12-14.

The decoded video signal passes from the post-processing filter 508 to the edge enhancer 516. The edge enhancer 516 detects and enhances edges found in images in the decoded video signal. As described above, it is quite common that the 35 encoding and decoding processes will degrade an edge in at least one image. An edge

5 is defined as a portion of an image separating two image portions of substantially identical intensity. For example, an image of the United States flag may include a substantially red portion next to a substantially white portion. However, the edge between the red portion and the white portion may be fuzzy or unclear. Animated images are especially susceptible to this type of edge degradation, because the
10 characteristics of animation video include sharp edges in the spatial image as well as sharp temporal transitions in a video sequence. The edge enhancer 516 is designed to detect a suspected edge (i.e., a candidate edge), determine whether the candidate edge is a true edge, and enhance the edge to create a sharper edge. Enhancing the edge can include modifying the intensity (e.g., luminance, chrominance) of one or more pixels
15 on or near the edge to make the edge more perceivable.

The filtered, enhanced, and decoded video stream is output from the edge enhancer 516 as video output 512. Likewise the audio decoder 510 produces the audio output 514. While the decoding system 500 of a exemplary embodiment of the present invention can be implemented with or without a post-processing filter, performance evaluations indicate that the specialized post-processing filter 508 improves the output of the edge enhancer 516. Accordingly, an exemplary embodiment of the present invention incorporates the functionality of the specialized post-processing filter with that of the edge enhancer to maximize the quality of the video output 512.

25 Figure 6a depicts an exemplary pixel matrix in enhanced and in unenhanced images. A pixel matrix 600 of an unenhanced image includes flaws that result in a fuzzy edge 602. The edge 602 is fuzzy, because pixels 604 that should be black (i.e., low image intensity) are, instead, represented as gray pixels (i.e., higher image intensity). Once enhanced, however, the enhanced pixel matrix 606 includes a
30 distinctive edge 608. Notably, the gray pixel 604 in the unenhanced pixel matrix 600 is associated with a low image intensity (i.e., black) as shown by pixels 610 in enhanced pixel matrix 606.

An edge in the unenhanced pixel matrix 600 can be detected by comparing adjacent pixels. Figure 6b depicts an exemplary pixel intensity graph illustrating the relationship between adjacent pixels in enhanced and in unenhanced

5 images. The intensity graph 650 depicts the intensity relationship between an edged pixel B and its adjacent pixels A and C. The intensity level is shown on the y-axis of the graph 650 and the pixel identification is shown on the x-axis of the graph. The intensity of pixel A is higher than the intensity of pixel B. Likewise, the intensity of pixel C is higher than the intensity of pixel B. Accordingly, B can be identified as a
10 candidate edge pixel. In this example, the pixel B has a lower luminance and/or chrominance than pixel A or pixel C. In a digitized image, the image may be examined on a pixel-by-pixel basis so that each pixel in the image can be compared to the adjacent pixels. When a pixel is detected having a lower intensity than both of its adjacent pixels, that pixel (i.e., the subject pixel) may be identified or classified as a
15 candidate edge pixel.

A candidate edge pixel may be converted to a true edge pixel, in certain conditions. For example, if one or more candidate pixels are adjacent to one another, the combination of these pixels may indicate the presence of a true edge. Likewise, the detection of three, adjacent candidate edge pixels represent an even higher likelihood that the candidate edge pixels are actually true edge pixels. The number of contiguous candidate edge pixels required to classify the candidate edge pixels as true edge pixels depends on various factors such as compression/decoding quality and the tolerance of a particular application for fuzzy edges. True edges are generally determined by a two-dimensional examination of an image. That is, when a
25 subject candidate edge pixel has been found, adjacent candidate edge pixels may be to the left or right or may be above or below the subject candidate edge pixel. Obviously, when two, adjacent candidate edge pixels have been found, a third candidate edge pixel may be found on any side of those pixels. In any event, it will be appreciated by those skilled in the art that a two-dimensional analysis should usually
30 be applied to determine whether one or more candidate edge pixels reside on a true edge.

In an exemplary embodiment of the present invention, the intensity of the subject pixel can be modified to make an edge more distinctive. Enhanced intensity graph 652 illustrates the relative intensities of three pixels associated with a
35 detected edge. The intensity of the subject pixel, pixel B, is significantly decreased

5 such that the slope of the graph between pixel A and pixel B is significantly increased. Likewise, the slope of the graph between pixel B and pixel C also is increased. Comparing the intensity graph 650 to the enhanced intensity graph 652, it can be seen that the difference in intensity between pixels A and B and pixels C and B has been substantially increased. This increased difference will tend to create a more
10 distinctive edge from a detected fuzzy edge.

In an exemplary embodiment of the present invention, an edge can be detected where the intensity of a subject pixel is less than the intensity of a left adjacent pixel and is less than the intensity of a right adjacent pixel. In an alternative embodiment, the subject pixel will only become classified as a candidate edge pixel if these requirements are met and if the difference between the intensity of the subject pixel and the intensity of the left adjacent pixel or the intensity of the right adjacent pixel is greater than a predetermined threshold. For example, if the pixel intensity difference is less than 20% of the full intensity range, the subject pixel may not be classified as a candidate edge pixel.
15

20 In an exemplary embodiment of the present invention, the subject pixel will not be enhanced, unless the subject pixel is classified as a candidate edge pixel and is classified as a true edge pixel. In an exemplary embodiment of the present invention, a true edge pixel is a candidate edge pixel that is immediately adjacent to at least two other candidate edge pixels. Those skilled in the art will appreciate that any
25 number of required adjacent candidate edge pixels may be used within the scope of the present invention.

Figure 7 is a flow chart depicting an exemplary method for examining and enhancing the pixels of a digitized image. The method begins with start block 700 and proceeds to step 702. At step 702, the first pixel is examined. The method then proceeds to decision block 704, wherein a determination is made as to whether the first pixel is a candidate edge pixel. If the first pixel is a candidate edge pixel, the method branches to decision block 706. If, on the other hand, the first pixel is not a candidate edge pixel, the method branches to decision block 710. At decision block 710, a determination is made as to whether the image includes any more unexamined pixels.
30 If the image does not include any more unexamined pixels, the method
35

5 branches to end block 714 and terminates. On the other hand, if the image includes more unexamined pixels, the method branches to step 712. At step 712, the next pixel is examined and the method proceeds back to decision block 704.

Returning now to decision block 704, if a determination is made that the examined pixel is a candidate edge pixel the method branches to decision block 10 706. At decision block 706, a determination is made as to whether the examined pixel is a true edge pixel. If the examined pixel is a true edge pixel, the method branches to step 708. As described above, in connection with Figure 6, this step may be performed by examining adjacent and contiguous pixels in two-dimensions to determine whether a candidate edge pixel is a true edge pixel.

15 At step 708, the true edge pixel is enhanced thereby enhancing the edge. The method then proceeds from step 708 to decision block 710. Likewise, if at decision block 706, a determination is made that the candidate edge pixel is not a true edge pixel, the method branches to decision block 710. The method proceeds from decision block 710 as described above. The flow chart depicted in Figure 7 is a broad
20 overview of an exemplary embodiment of the present invention. The remaining figures are provided in connection with more specific description of the components of this broad overview.

Figure 8 is a flow chart depicting an exemplary method for detecting an edge in an image. The method of Figure 8 begins at start block 800 and proceeds to step 802. At step 802, the intensity of a subject pixel is compared with the intensity of a left adjacent pixel. For the purposes of this description, it is assumed that the pixels of an image are examined on a pixel-by-pixel basis in a left-to-right fashion. Those skilled in the art will appreciate that this is an arbitrary choice and that the pixels of an image can be compared in a variety of methods, within the scope of the present invention.

The method proceeds from step 802 to decision block 804. At decision block 804, a determination is made as to whether the intensity of the subject pixel is less than the intensity of the left adjacent pixel. If the intensity of the subject pixel is not less than the intensity of the left adjacent pixel, the method branches to end block

5 **816** and terminates. If, on the other hand, the intensity of the subject pixel is less than the intensity of the left adjacent pixel, the method branches to step **806**.

At step **806**, the intensity of the subject pixel is compared with the intensity of the right adjacent pixel. The method proceeds from step **806** to decision block **808**. At decision block **808**, a determination is made as to whether the intensity of the subject pixel is less than the intensity of the right adjacent pixel. If the intensity of the subject pixel is not less than the intensity of the right adjacent pixel, the method branches to end block **816** and terminates. If, on the other hand, the intensity of the subject pixel is less than the intensity of the right adjacent pixel, the method branches to decision block **810**.

15 At decision block **810**, a determination is made as to whether the intensity difference between the subject pixel and the right adjacent pixel is greater than a predetermined threshold. As described in connection with Figure 6, the threshold may be determined based on various constraints including the acceptable tolerance for fuzzy edge in a particular application. If the intensity difference between the subject pixel and the right adjacent pixel is not greater than the predetermined threshold, the method branches to decision block **812**. If, on the other hand, the intensity difference between the subject pixel and the right adjacent pixel is greater than the predetermined threshold, the method branches to step **814**. At step **814**, the subject pixel is classified as a candidate edge pixel. The method then proceeds to end block **816** and terminates.

20 At decision block **812**, a determination is made as to whether the intensity difference between the subject pixel and the left adjacent pixel is greater than a predetermined threshold. If the intensity difference between the subject pixel and the left adjacent pixel is not greater than the predetermined threshold, the method branches to end block **816** and terminates. If, on the other hand, the intensity difference between the subject pixel and the left adjacent pixel is greater than the predetermined threshold, the method branches to step **814** and the subject pixel is classified as a candidate edge pixel. The method proceeds from step **814** to end block **816** and terminates.

5 Accordingly, the method of Figure 8 detects an edge by comparing the intensity of a subject pixel with that of adjacent pixels. In cases where the subject pixel has a lower intensity than that of the adjacent pixels, the method determines whether the difference between the subject pixel and at least one of the adjacent pixels is greater than a predetermined threshold. Where this is the case, the subject pixel is
10 classified as a candidate edge pixel.

Figure 9 is a flow chart depicting an exemplary method for detecting and enhancing true edge pixels. The method of Figure 9 begins with start block 900 and proceeds to decision block 902. At decision block 902, a determination is made as to whether a subject candidate edge pixel has an adjacent candidate edge pixel. If the subject candidate edge pixel does not have an adjacent candidate edge pixel, the method branches to end block 910 and terminates. If, on the other hand, a determination is made at decision block 902 that the subject candidate edge pixel has an adjacent candidate edge pixel, the method branches to decision block 904.

At decision block 904, a determination is made as to whether an adjacent candidate edge pixel has a second adjacent candidate edge pixel. If a determination is made that the adjacent candidate edge pixel does not have a second adjacent candidate edge pixel, the method branches to end block 910 and terminates. If, on the other hand, the adjacent candidate edge pixel is determined to have a second adjacent candidate edge pixel, the method proceeds to step 906. Notably, the subject candidate edge pixel need not be adjacent to the second adjacent candidate edge pixel. In an exemplary embodiment, however, the three pixels should be contiguous in one dimension or two dimensions.

At step 906, the subject pixel, the adjacent pixel, and the second adjacent pixel are classified as true edge pixels. This classification is appropriate where the method has identified three, contiguous candidate edge pixels. This indicates that the edge is a true edge, as opposed to an image flaw created by, for example, noise. The method proceeds from step 906 to step 908. At step 908, the intensity slope for the subject pixel, the adjacent pixel, and the second adjacent pixel is increased. This step is performed to enhance the pixels that have been classified as true edge pixels. Increasing the intensity slope causes the edge formed by the three

5 pixels to be more distinctive, as described above in connection with Figure 6. The method proceeds from step 908 to end block 910 and terminates.

Figure 10 is a graph depicting an embodiment of the present invention in which the intensity slope adjustment is adapted to match the image quality of an unenhanced image. In this embodiment of the present invention, the modifications 10 made to the intensity slope can be adapted to match the characteristics of a particular image. Figure 10 shows a graph depicting the slope adjustment ($f(x)$) in relation to an image quality (x). The slope adjustment is depicted on the y-axis 1002 and the image quality is graphed along the x-axis 1004. The graph 1000 shows that the most aggressive slope adjustment is made when the image quality is average (i.e., between 15 low quality and high quality), as identified by point 1010. However, when the image quality is low, the slope adjustment is also reduced, as identified by point 1006. Finally, when the image quality is high, the slope adjustment is also reduced, as identified by point 1008.

When the image quality is high, it is assumed that less edge enhancement (i.e., less slope adjustment) needs to be made to enhance the high quality image. Therefore, the identification and enhancement of a true edge is not needed as much as when processing an average quality image. On the other hand, a 20 low quality image typically contains many image flaws. Often, these flaws will be falsely classified as a true edge and an unneeded edge enhancement will be performed 25 on the flaw. Such errant edge enhancement will only serve to exaggerate the flaw. Accordingly, for low quality images, the slope adjustment is reduced to avoid counterproductive edge enhancement.

Figure 11 is a graph depicting an adaptive slope adjustment utilized in another embodiment of the present invention. The graph 1100 depicts a relationship 30 between the slope adjustment ($f(q)$) on the y-axis 1102 and the background intensity (q) on the x-axis 1104. The graph of Figure 11 represents the philosophy that edge detection and enhancement is most suitable for pixels in dark or light backgrounds. More slope adjustment, therefore, is appropriate where an edge is detected in a portion of an image having a high background intensity, as identified by point 1108. 35 Likewise, a higher slope adjustment is appropriate for an edge detected in a portion of

5 an image having a low background intensity, as identified by point 1106. On the contrary, for an edge detected in a portion of an image having an average background intensity, the slope adjustment can be reduced, as identified by point 1110.

Figure 12a is a block diagram depicting the presence of blockiness noise in an unenhanced picture. Blockiness noise can be created as a byproduct of the compression process. Most compression techniques divide a digitized image into blocks of pixels. It is typical that a compression technique will use 8-by-8-pixel blocks. Each block is compressed and decoded individually. As a result, it is common that pixels on the edges of each block no longer fit with the edge pixels of an adjacent pixel block. That is, because the edge pixels are individually processed, they 10 may be decoded to look substantially different than an adjacent edge pixel that is part of another pixel block. Consequently, the edges of an image's pixel blocks may be 15 perceivable. This phenomenon is well known and is called blockiness because the image appears to be formed of blocks rather than having a seamless appearance. Various filters have been devised to smooth blockiness. Many of these techniques 20 can be used within the scope of the present invention to reduce blockiness. However, an exemplary embodiment of the present invention implements an adaptive method to refine the application of a blockiness filter.

Referring now to Figure 12a, an 8-by-8-pixel block 1200 is depicted having edge pixels including pixels x_0 and x_1 . Blocks x_2 and x_3 are edge pixels for 25 adjacent pixel blocks (not shown entirely). Conventional blockiness filters can be used to smooth the differences between x_0 and x_2 and between x_1 and x_3 . However, the mechanical application of a blockiness filter will simply cause, for example, x_1 to look more like x_3 . This is usually acceptable, but in some instances, x_1 and x_3 are 30 meant to be significantly different. In such instances, a conventional blockiness filter can be counter-productive.

In an exemplary embodiment of the present invention, the performance of a blockiness filter is adapted, based on the differences between adjacent edge pixels. Referring now to Figure 12b, a graph 1202 depicts the amount of pixel modification $f(d)$ as a function of the differences (d) between the pixels. The 35 difference between the pixels can be determined in a variety of ways. One way is to

5 compare the image intensity of the pixels (e.g., luminance, chrominance). In an exemplary embodiment of the present invention, the difference (d) is determined by the formula:

$$d = (x_3 - x_1)/4$$

10 where x_1 and x_3 are the image intensities of corresponding, adjacent edge pixels from adjacent pixel blocks. The image intensity that will be assigned to the pixel to smooth the edges is given by the formula:

$$x_1' = x_1 + f(d)$$

15 where x_1' is the image intensity of pixel x_1 following processing by the blockiness filter. However, in an exemplary embodiment of the present invention, a threshold value (ϵ) is used to limit the application of the blockiness filter. Where the difference (d) is greater than the threshold value (or less than the negative threshold value), then the blockiness filter of an exemplary embodiment of the present invention does not smooth the subject pixel. This relationship is represented by the plot of the graph 1202 of Figure 12.

20 When the difference between the compared pixels is dramatic, the blockiness filter will not affect those pixels. This improved blockiness filter may be implemented as part of a post-processing filter (e.g., element 508 of Figure 5) or may be implemented as a separate filter. In any event, the blockiness filter can reduce the occurrence of undesirable smoothing of pixels. In particular, the adaptive blockiness filter of an exemplary embodiment of the present invention avoids smoothing edges in an image that may cause an edge enhancer (e.g., element 516 of Figure 5) to fail to detect an edge in the image. Moreover, the adaptive blockiness filter of an exemplary embodiment of the present invention avoids smoothing an edge that will only be subsequently enhanced by an edge enhancer. Those skilled in the art will appreciate 25 that although the operation of the blockiness filter is described in connection with the edge enhancer, the operation of these components may be kept separate and independent.

30 Figure 13 is a block diagram depicting the adaptive performance of a salt-and-pepper noise filter that is an exemplary embodiment of the present invention. 35 Like blockiness, salt-and-pepper noise (SP noise) can be created as a byproduct of the

5 compression process. SP noise is caused by image defects that are present in the frames of a video stream (or other image series). As the frames are displayed, the defects appear randomly on the screen. Various filters have been devised to eliminate SP noise. Many of these techniques can be used within the scope of the present invention to reduce or eliminate SP noise. However, an exemplary embodiment of
10 the present invention refines the application of an SP noise filter.

Referring now to Figure 13, a 3-by-3-pixel block 1300 is depicted having a center pixel, x_0 . Pixel x_0 is the subject pixel, meaning that pixel x_0 is being considered for smoothing. Conventional SP noise filters can be used to smooth the differences between x_0 and one or more of the surrounding pixels. However, the
15 mechanical application of an SP noise filter will simply cause x_0 to look more like one of the other pixels. This is often acceptable, but in some instances, this may be too aggressive an alteration of x_0 . Moreover, if pixel x_0 is meant to be significantly different than the other pixel(s), then it may result in an overly aggressive smoothing of x_0 . In such instances, a conventional SP noise filter can be counter-productive to
20 the objective of post-processing. In one embodiment of the present invention, only edge pixels will be chosen for SP noise reduction/elimination.

In an exemplary embodiment of the present invention, the performance of an SP noise filter is adapted, based on the characteristics of the surrounding, adjacent pixels. Referring again to Figure 13, the image intensity of the surrounding
25 pixels (e.g., luminance, chrominance) can be used to determine an appropriate smoothing of pixel x_0 . In an exemplary embodiment of the present invention, an image intensity median (z) can be determined among the subject pixel and each surrounding, adjacent pixel in each of the four directions identified in Figure 13. Thus, z is determined by the formula:

30
$$z = \{\text{median value of pixels in direction } l\}$$

where $l = 1, 2, 3$, and 4 . The image intensity that will be assigned to the subject pixel is given by the formula:

$$x_0' = \text{Median}\{\max(z_l), \min(z_l), x_0\}$$

where x_0' is the image intensity of pixel x_0 following processing by the SP noise filter.
35 Accordingly, the adjusted image intensity, x_0' , is the median of the maximum

5 intensity found, the minimum intensity found, and the subject pixel's original intensity, x_0 . Thus, SP noise is reduced, but in a manner that is adaptive to the environment (i.e., background) in which the subject cell resides.

Figure 14a is a block diagram depicting an exemplary group of adjacent pixels that may be examined and filtered for mosquito noise by an exemplary embodiment of the present invention. Like blockiness and salt-and-pepper noise (SP noise), mosquito noise can be created as a byproduct of the compression process. Mosquito noise is caused by image defects that are present in the frames of a video stream (or other image series). As the frames are displayed, the defects appear to flicker around the screen, thus giving the appearance of mosquitoes. Various filters have been devised to eliminate mosquito noise. Many of these techniques can be used within the scope of the present invention to reduce or eliminate mosquito noise. However, an exemplary embodiment of the present invention implements an adaptive method to refine the application of a mosquito noise filter.

Referring now to Figure 14a, a 3-by-3 pixel block **1400** is depicted having nine pixels, x_0 - x_8 , eight of which surround pixel x_0 . Pixel x_0 is the subject pixel, meaning that pixel x_0 is being considered for smoothing. Blocks x_1 - x_8 are surrounding, adjacent pixels. Conventional mosquito noise filters can be used to smooth the differences between x_0 and one or more other pixels. However, the mechanical application of a mosquito noise filter will simply cause, for example, x_0 to look more like x_3 . This is often acceptable, but in some instances, this may be too aggressive an alteration of x_0 . Moreover, if x_3 is meant to be significantly different than x_0 , then it may result in an overly aggressive smoothing of x_0 . In such instances, a conventional mosquito noise filter can be counter-productive to the objective of post-processing.

In an exemplary embodiment of the present invention, the performance of a mosquito noise filter is adapted, based on the characteristics of the surrounding, adjacent pixels. Referring now to Figure 14b, a graph **1402** depicts the amount of pixel modification $f(d)$ as a function of the differences (d) between the subject pixels and the surrounding, adjacent pixels. The difference between the pixels can be determined in a variety of ways. One way is to compare the image intensity of the

5 pixels (e.g., luminance, chrominance). In an exemplary embodiment of the present invention, the difference (d) between the subject pixel and each surrounding, adjacent pixel is determined by the formula:

$$d = (x_0 - x_i)$$

10 where x_0 and x_i are the image intensities of the subject pixel and of an adjacent pixel, respectively. The image intensity that will be assigned to the pixel to smooth the edges is given by the formula:

$$x_0' = x_0 - (f(d_1) + f(d_2) + f(d_3) + f(d_4) + f(d_5) + f(d_6) + f(d_7) + f(d_8))/8$$

15 where x_0' is the image intensity of pixel x_0 following processing by the mosquito noise filter. However, in an exemplary embodiment of the present invention, a threshold value (ϵ) is used to limit the application of the mosquito noise filter. Where the difference (d) is greater than the threshold value (or less than the negative threshold value), then the mosquito noise filter of an exemplary embodiment of the present invention does not smooth the subject pixel. This relationship is represented by the plot of the graph 1402 of Figure 14.

20 When the difference between the compared pixels is dramatic, the mosquito noise filter will not affect those pixels. This improved mosquito noise filter may be implemented as part of a post-processing filter (e.g., element 508 of Figure 5) or may be implemented as a separate filter. In any event, the mosquito noise filter can reduce the occurrence of undesirable smoothing of pixels. In particular, the adaptive 25 mosquito noise filter of an exemplary embodiment of the present invention avoids smoothing edges in an image that may cause an edge enhancer (e.g., element 516 of Figure 5) to fail to detect an edge in the image. Those skilled in the art will appreciate that although the operation of the blockiness filter is described in connection with the edge enhancer, the operation of these components may be kept separate and 30 independent.

Although the present invention has been described in connection with various exemplary embodiments, those of ordinary skill in the art will understand that many modifications can be made thereto within the scope of the claims that follow. For example, the inventors contemplate that the various embodiments of the present 35 invention could be utilized in a wide variety of applications, including, but not limited

5 to, images used in animation, computerized banners, real-time streaming video, stored video, and gaming graphics. Accordingly, it is not intended that the scope of the invention in any way be limited by the above description, but instead be determined entirely by reference to the claims that follow.